REPAIR OF LOCALIZED DEFECTS IN MULTILAYER-COATED RETICLE BLANKS FOR EXTREME ULTRAVIOLET LITHOGRAPHY

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BLANKS FOR EXTREME ULTRAVIOLET LITHOGRAPHY

BACKGROUND OF THE INVENTION

5   Field of the Invention

The present invention relates to minimizing defects in the components produced by an extreme ultraviolet lithography (EUVL) system, and more specifically, it relates to a method for repairing defects in the multilayer coating of an EUVL reticle.

Description of Related Art

The reticle blank to be used in an extreme ultraviolet lithography (EUVL) system is expected to consist of a thick substrate coated with a reflective multilayer film. This multilayer film is subsequently covered with a patterned absorber layer to form the EUVL reticle. See C.W. Gwyn, R. Stulen, D. Sweeney, and D. Attwood, "Extreme Ultraviolet Lithography", J. Vac. Sci. Technol. B 16, 3142 (1998). When the reflective multilayer coating is deposited on substrate imperfections such as particles, pits or scratches, the layer structure of the multilayer film is perturbed, resulting in mounds or depressions in the contour of the layers. See P.B. Mirkarimi, S. Bajt, and D.G. Stearns, "Mitigation of Substrate Defects in Reticles Using Multilayer Buffer Layers", U.S. Patent now U.S. PATENT No. 6,319,635 Application Serial No. 09/454,715, incorporated herein by reference. AR(3/13/03) These defects produce unacceptable intensity variations in the lithographic image when they exceed a lateral dimension of about 30 nm, and a height variation of more than about 1 nm. See T. Pistor, Y. Deng, and A. Neureuther, "Extreme Ultraviolet Mask Defect Simulation – Part II", J. Vac. Sci. Technol. B, to be published in the November/December 2000 issue.

The above-incorporated patent application proposes using buffer layers to mitigate the growth of multilayer phase defects from small substrate particles and features that cannot be detected by standard inspection tools. The buffer layer concept exploits the smoothing properties of specially designed films

to reduce the size of the substrate perturbations to a level at which they will not nucleate a critical (i.e., printable) phase defect in the multilayer reflective coating. Although this approach should greatly reduce the population of phase defects, it must be expected that a few critical phase defects will always be present. These could arise, for example, from the contamination of the top surface of the buffer layer. Hence it is essential that a process be developed for repairing a small number of phase defects in the Mo/Si multilayer reflective coating on a EUVL mask. The problem with repairing the multilayer reflective coating is that it is fundamentally incompatible with the current mask repair technology. The current technology involves repairing defects in the metal absorber layer by locally removing or depositing material; however, the repair of the multilayer film must consist of correcting the local deformation of the layers within the film.

U.S. Patent No. 5,272,744, titled "Reflection Mask", by M. Itou, H. Oizumi, and S. Moriyama, granted 12/21/93 (Itou et al.) describes a special reticle for x-ray and extreme ultraviolet lithography that is provided to facilitate the repair of multilayer defects. This reticle comprises two multilayer film stacks separated by an Au layer and is in contrast to the conventional reticle design incorporating patterned absorber layers on a multilayer film or the other design of a patterned multilayer on an absorber. (See also U.S. Patent No 5,052,033 titled "Reflection Type Mask" by T. Ikeda et al.) There are some disadvantages to the Itou et al. approach, including (i) their reticle is more difficult and expensive to

fabricate than other designs, (ii) the introduction of the Au layer will likely

introduce additional roughness in the reflective overlayer, reducing the

reflectance and throughput of the lithography system, (iii) their repair process is

not a local one and involves covering the entire reticle blank with resist, etc.,

5   which could lead to new particulates/defects, and (iv) it is uncertain whether

their method will work in a practical sense since it requires extreme control of

the Au deposition and various etching processes so that a phase defect does not

result from the multilayer defect repair process.

It is desirable that techniques be provided for the repair of multilayer

10   film defects in reticles for use in extreme ultraviolet lithography.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a method for

repairing defects in a multilayer coating that is deposited onto a reticle blank

used in an extreme ultraviolet lithography (EUVL) system.

15   Other objects of the invention will be apparent to those skilled in the

art based on the teachings herein.

A localized energy source is used for depositing energy in a multilayer

coating of a reticle blank. The energy is deposited in the vicinity of the defect in

a controlled manner and with high lateral spatial resolution. This can be

20   accomplished using a focused electron beam, focused ion beam, focused

electromagnetic radiation or through direct contact with an electrode. If the multilayer comprises an appropriate material combination, the absorbed energy will cause a structural modification (e.g., interdiffusion at the layer boundaries), producing a localized change in the film thickness. By adjusting the energy dose,

5   the change in film thickness can be controlled with sub-nanometer accuracy. Localization of the energy deposition controls the lateral spatial resolution of the thickness modification. The film thickness is adjusted locally to correct the perturbation of the reflected field. For example, in the case where the structural modification is a contraction of the film, the repair of a defect consists of

10   flattening a mound or spreading out the sides of a depression. The defect repair can be applied directly to the reflective multilayer coating or to a buffer layer consisting of a multilayer film deposited below the reflective multilayer. Finite element simulations for the case of an electron beam impinging on a Mo/Si multilayer film indicate that this is a viable defect repair technique for EUVL

15   reticle blanks.

This invention has the potential to impact current extreme ultraviolet lithography (EUVL) system development and to impact government programs such as ASCII. There is a strong commercial driving force for increased miniaturization in electronic devices, and hence an extreme ultraviolet

20   lithography (EUVL) tool has significant commercial potential. To be economically viable, this technology requires a nearly defect-free reticle.

Commercial integrated circuit manufacturers currently rely on defect repair techniques to obtain reticles with sufficiently low defect densities; however, these repair techniques cannot be applied to EUVL reticles.

BRIEF DESCRIPTION OF THE DRAWINGS

5   Figure 1A shows a multilayer film before exposure to a focused beam.

Figure 1B shows a multilayer film after exposure to a focused beam.

Figure 2 shows the results of a finite element simulation of the deformation of a Mo/Si multilayer film.

Figure 3 illustrates that the size of a depression at the multilayer

10   surface can be controlled by controlling the exposure time.

Figure 4 shows the temperature profile obtained for an electron beam of current I=3 µA and voltage V = 10 kV.

Figure 5 is a plot of the temperature as a function of radial position on the top surface of the multilayer.

15   Figure 6 shows the variation of temperature as a function of depth z at the center of the electron beam (r=0).

Figure 7 shows a contour plot of the thickness of the silicide interlayer after an electron beam exposure of 10 ms.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is a method to repair defects in the multilayer-coated reticles used in extreme ultraviolet lithography systems. The method consists of depositing energy in the multilayer coating in the vicinity of the

5   defect with high lateral spatial resolution. This can be accomplished using a focused electron beam, focused ion beam, focused electromagnetic radiation or through direct contact with an electrode. If the multilayer film consists of Mo/Si or another appropriate material combination, the absorbed energy will cause a structural modification, producing a localized change in the film thickness. An

10   appropriate material combination would be defined by materials that undergo structural modification at elevated temperatures that results in a local change in density. This could be due to the formation of a compound, as in the case of Mo/Si, or could be simply a phase transformation. Note that either an increase or decrease in the density is useable. Mo/Si has an increase in density, thereby

15   producing a film contraction. If the density decreases upon heating then the invention would be used to expand the film in the region of valleys and smooth the edges in the region of hills. The localized change in the film thickness is illustrated schematically in figures 1A and 1B, which show the multilayer film before (Fig. 1A) and after (Fig.1B) exposure to the focused beam 10 in the case

20   where the structural modification is a contraction. The change in film thickness can be controlled with sub-nanometer accuracy by adjusting the energy dose.

The lateral spatial resolution of the thickness modification is controlled by the localization of the energy deposition. The film thickness is adjusted locally to correct the perturbation of the reflected field. For example, in the case where the structural modification is a local contraction of the film, the repair of a defect consists of flattening a mound or spreading out the sides of a depression. The defect repair can be applied directly to the reflective multilayer coating or to a buffer layer consisting of a multilayer film deposited below the reflective multilayer. This invention can be used to repair multilayer defects in reticle blanks or in fully patterned reticles, since the highest temperature used in the repair process can be maintained well below the melting temperature of the metal absorber layer.

In order to assess the viability of the present invention, finite element simulations were performed for the case of an electron beam impinging on a localized area of a Mo/Si multilayer film. In this case the structural modification is a local contraction of the multilayer period due to silicide formation, which produces an indentation in the film in the vicinity of the electron beam. Figure 2 shows the results of a finite element simulation of the deformation of a Mo/Si multilayer film 20 produced by a 10 msec exposure to an electron beam 22 of radius 25 nm, energy 10 kV, and current 3 $\square$A. The depression at the surface is 12 nm, yet the contraction of each multilayer period is only 0.5 nm. This modification of the multilayer structure can be used to correct the phase of the

reflected field without significantly altering the reflected amplitude. The size of

the depression at the surface can be controlled by controlling the exposure time,

as shown in Figure 3. The lines at 30, 32 and 34 represent exposure times of 1 ms,

3 ms and 10 ms respectively. More information on these simulations is described

5   below.

More specifically, finite element analysis was used to simulate the

temperature increase in a Mo/Si multilayer film due to the injection of current by

an electron beam. The calculations were performed using the commercial

FlexPDE software sold by PDE Solutions, Inc. See www.pdesolutions.com. The

10   Mo/Si multilayer film was modeled in cylindrical coordinates (2D) as a disk of

thickness 280 nm and radius 10 μm on a Si substrate of thickness 1.12 μm. The

multilayer film, which actually is composed of 40 Mo/Si periods each having a

thickness of 7.0 nm, was treated as a single isotropic film for the purpose of the

FEM modeling. The material properties of the Mo/Si film and the Si substrate

15   are listed in Table I.

TABLE I. Values for the thermal conductivity K, the mass density p, the specific
heat cp and the conductivity σ used in the FEM modeling.

Material	$\square$(W/cm-°K)	$\square$(gm/cm^3)	c_P(J/gm - °K)	$\sigma(1/\Omega - cm)$
Mo/Si ML Film	1.45	5.48	0.53	1x10^4
Si substrate	1.49	2.33	0.71	1

The time-dependent temperature profile T(r,z;t) within the multilayer

film was determined by solving the thermal diffusion equation:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\kappa\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\kappa\frac{\partial T}{\partial z}\right)-\rho c_P\frac{\partial T}{\partial t}+H(r,z;t)=0 \qquad (1)$$

Here H is the heat source. The electron beam voltage was chosen to be

5   sufficiently high (10 kV) so that the electron range would approximately match

the thickness of the multilayer film. Then it was assumed that the energy was

deposited uniformly through the film, within a cylinder of radius r0=25 nm.

(This oversimplified picture neglects the scattering of the electrons within the

film, which could be significant). In this model the heat deposited by the

10   electron beam per unit volume was given by,

$$H=\frac{IV}{\pi r_0^2 \tau} \qquad (2)$$

Here I and V are the respective current and voltage of the electron beam and τ is

the thickness of the multilayer film.

The time required for heat to diffuse a distance x is given by $x^2\rho c_P/\kappa$.

15   Inserting the values from Table I, it is seen that heat diffuses a micron in 20 ns.

Hence, over the physical dimensions of this problem, the transient temperature

dependence only lasts for tens of nanoseconds. Since such short timescales are

not of interest, Eq. (1) was simplified by dropping the dT/dt term and just solved

for the steady state temperature profile. The boundary conditions used in the

calculations were that the bottom and sides of the substrate and the sides of the

5   multilayer film were maintained at a constant ambient temperature of 300°K.

These surfaces were also defined to be electrical ground (V = 0). The top surface

of the multilayer film was assumed to be thermally insulated (i.e., radiative

cooling was neglected).

The current density was adjusted to produce peak temperatures

10   sufficiently high (> 800°K) to activate the silicide formation that causes the

contraction of the multilayer film. The temperature profile obtained for an

electron beam of current I=3 μA and voltage V = 10 kV is shown in Fig. 4. The

temperature on the top surface is plotted in Fig. 5 as a function of radial position.

The variation of temperature as a function of depth z at the center of the electron

15   beam (r=0) is plotted in Fig. 6. It can be seen that the temperature has a

maximum value of 910°K at the top surface and decreases only to 880°K half way

through the thickness of the film. Hence the heating is fairly uniform in depth

due to the penetration of the electron beam. Fig. 5 shows that the temperature

falls off rapidly in the radial direction, reducing to 700°K within 50 nm of the

20   center of the electron beam.

Once the temperature profile is known, it is straightforward to

calculate the contraction of the multilayer film due to silicide formation. The

reaction of Mo and Si at the interfaces is rate limited by thermally activated

interdiffusion (See "Silicide Layer Growth Rates in Mo/Si Multilayers", R.S.

5   Rosen, D. G. Stearns, M. A. Viliardos, M. E. Kassner, S. P. Vernon and Y. Cheng,

Appl. Optics 32, 6975 (1993), incorporated herein by reference.) The width of the

interlayer increases with time according to:

$$w^2 = w_0^2 + 2Dt \qquad (3)$$

Here w_0 =1.0 nm is the starting thickness of the interlayers in as-deposited films.

10   The interdiffusion coefficient D is given by,

$$D = D_0 \exp(-E_A / kT) \qquad (4)$$

Where D_0 = 50 cm²/s and E_A = 2.4 eV for Mo/Si multilayer films. The formation

of the silicide interlayer involves densification that leads to a contraction of the

multilayer period. The local change in the period is given by,

15                          $$\Delta\Lambda = \Lambda_0 - \alpha(w - w_0) \qquad (5)$$

Here α is the contraction factor that depends on the particular silicide compound that is formed. In this study, α = 0.38 is used, which corresponds to the contraction that occurs upon the formation of MoSi$_2$.

The growth of the silicide interlayer has an approximately square root dependence on the time that the film is subjected to heating, which will be referred to as the exposure time. Note that because the thermal response is so rapid, the transient heating and cooling times can be neglected. Contour plots showing the thickness of the silicide interlayer after an exposure of 10 ms are presented in Fig. 7 for the case of electron beam heating. The interlayer has a maximum thickness at the surface of the film in the center of the current injection (r=0), and is approximately twice as thick as the as-deposited interlayer. It is evident that the electron beam creates significant interlayer growth nearly half way through the entire thickness of the film. This is of course due to the penetration of the electron beam, and the fairly uniform heating through the thickness of the film. Because the interlayer growth is in an activated process, it is only significant in those regions reaching temperatures greater than ~ 800°K.

The local contraction of the multilayer period produces an indentation in the film in the vicinity of the electron beam. The structural deformation in the Mo/Si multilayer film resulting from a 10 ms exposure (I= 3 □A, V=10kV) is shown in Fig. 2. Although the depression at the surface is 12 nm deep, the contraction of each multilayer period, ΔΛ , is less than 0.5 nm. Consequently the

primary effect of such a deformation on the EUV reflectivity of the multilayer film will be to cause a local phase perturbation. For larger deformations there will also be a decrease in the reflectivity due to the decrease in contrast at the multilayer interfaces. Note also that the lateral width of the deformation is

5   contained within the region of the electron beam. The depth of the deformation is most easily controlled by adjusting the exposure time. Again, this is shown in Fig. 3, where the profile of the top surface of the film is plotted for exposure times of 1, 3 and 10 ms. It is apparent that by adjusting the exposure time and the footprint, the detailed shape of the deformation and the corresponding phase

10   shift can be accurately controlled.

These results show that an electron beam of moderate voltage (~10 kV) can be used to contract the period of a Mo/Si reflective coating within a small spot defined basically by the footprint of the beam. (For Mo/Si, the key physical requirement on the energy deposition is the spatial resolution, i.e., small spot

15   size, and energy sufficient to raise the temperature by hundreds of degrees. In the case of Mo/Si this works out to a deposited power in the range of 1 – 100 mW.) The contraction of the period, due to thermally activated silicide formation at the multilayer interfaces, occurs through approximately half the thickness of the film (20 periods). This produces a controllable indentation at the

20   top surface having a depth that can exceed 10 nm Since the film contraction generated by the electron beam is distributed over many periods, the primary

effect of the deformation on the EUV reflectivity is a local phase shift of the reflected field. Bumps due to coating over particles can be repaired by directly writing on top of them to shrink the film back to its correct position. Indentations due to coating over pits and scratches could be repaired by

5   contracting the film at the edges and thereby smooth out the defect to mitigate the phase contrast. In fact, it might indeed be possible to use this technique to repair the Mo/Si multilayer film underneath an existing metal absorber layer, since the metal layer should not be affected by exposure to these temperatures.

The requirements of microamps of current at 10 kV are difficult to

10   achieve within a spot size of ~50 nm. One solution is to use field emission from a carbon nanotube. These nanotubes are typically tens of nanometers in diameter and are stable, high current field emitters capable of delivering microamps of current. (See A.G. Rinzler, J. H. Hafner, P. Nikolaev, L. Lou, S. G. Kim, D Tomanek, P. Nordlander, D. T. Colbert and R. E. Smalley, "Unraveling

15   Nanotubes: Field Emission from an Atomic Wire", Science 269, 1550 (1995) incorporated herein by reference. The nanotube could be integrated into the head of a scanning probe microscope, and proximity focusing could be used to steer the extracted current into a small spot on the surface of the film. The scanning probe microscope would be used to locate and monitor the repair of the

20   mask defect. Examples of carbon nanotubes are described in copending U.S. Patent Application Serial No. __/___,___, titled "A High-Current, High-Voltage,

Small Diameter Electron Beam Source Obtained By Field Emission From, And

Used In Close Proximity To, A Single Carbon Nanotube" filed on the same day as

the present application and incorporated herein by reference.

The foregoing description of the invention has been presented for

purposes of illustration and description and is not intended to be exhaustive or

to limit the invention to the precise form disclosed. Many modifications and

variations are possible in light of the above teaching. The embodiments were

chosen and described to best explain the principles of the invention and its

practical application to thereby enable others skilled in the art to best use the

invention in various embodiments and with various modifications suited to the

particular use contemplated. The scope of the invention is to be defined by the

following claims.